A search for correlations of TeV γ-rays with ultra-high energy cosmic rays

C. W. Akerlof[3], S. Biller[4], P. Boyle[2], J. Buckley[1], D. A. Carter-Lewis[5], M. Catanese[5], M. F. Cawley[6], V. Connaughton[1,10], D. J. Fegan[2], J. Finley[7], J. Gaidos[7], A. M. Hillas[4], F. Krennrich,[5], R. C. Lamb[5], R. Lessard[2], J. McEnery[2], G. Mohanty[5], N. A. Porter[2], J. Quinn[2], A. Rodgers[4], H. J. Rose[4], F. Samuelson[5], M. S. Schubnell[3], G. Sembroski[7], R. Srinivasan[7], T. C. Weekes[1], and J. Zweerink[5].

[1]CfA - Whipple Observatory, P.O. Box 97, Amado, AZ 85645

[2]University College Dublin, Physics Department, Belfield, Dublin 4, Ireland

[3]University of Michigan, Department of Physics, Randall Laboratory, Ann Arbor, MI 48109-1120

[4]University of Leeds, Department of Physics, Leeds LS2 9JT, United Kingdom

[5]Iowa State University, Department of Physics & Astronomy, Osborn Drive, Ames, Iowa 50011

[6]St.Patrick's College, Department of Experimental Physics, Maynooth, Co Kildare, Ireland

[7]Purdue University, Department of Physics, Lafayette, IN 47907

[10]Contact address: NASA Marshall Space Flight Center, ES 84, AL 35812

ABSTRACT

A search was conducted for TeV γ-rays emitted from the direction of the ultra-high energy cosmic ray detected by the Fly's Eye Experiment with $E \sim 3 \times 10^{20}$ eV. No enhancement was found at a level of $10^{-10}\gamma/\text{cm}^2$-sec for $E > 350$ GeV. This upper limit is consistent with theoretical estimates based on topological defects as sources of UHE cosmic rays. An upper limit was also set for the flux of TeV gamma rays from 3C147, the most prominent AGN in the error box.

1. Introduction

The surprising discovery of ultra-high energy (UHE) cosmic rays with $E > 10^{20}$ eV poses significant questions about how such particles can reach energies substantially in excess of the Greisen-Zatsepin-Kuz'min cutoff (Greisen 1966; Zatsepin & Kuz'min 1966) imposed by interactions with the cosmic microwave background radiation. If these particles are accelerated in relativistic shock fronts in a manner similar to the standard models for lower energy cosmic rays (Blandford 1978; Legage 1983; Bell 1978), the physical constraints are difficult to reconcile with what we know about possible acceleration sites on distance scales of 40 Mparsecs. This has suggested to several authors (Bhattacharjee 1990, Bhattacharjee et $al.$ 1992, Aharonian et $al.$ 1992, Sigl et $al.$ 1994) that a new "non-acceleration" mechanism is at work such as the decay of GUT scale topological defects with characteristic masses of the order of 10^{25} eV. A second possible origin for UHE cosmic rays is gamma-ray bursts (Milgrom & Usov 1995, Vietri 1995, 1996, Miralda-Escudé & Waxman 1996); Waxman (Waxman 1995) has pointed out that UHE cosmic rays and gamma-rays from GRBs have comparable fluences at the Earth, the possible consequence of energy equipartition. Although no one knows what the physical mechanism of gamma-ray bursts really is, it remains conceivable that these objects could also accelerate charged particles to ultrarelativistic energies.

Since the lifetime of superenergetic cosmic rays is limited to 10^8 years and the magnetic rigidity is extremely high, it is likely that the sources of this radiation lie close to the arrival directions measured on Earth. This suggests that a search for TeV gamma-ray counterparts might offer some chance of detection. The optical depth for TeV photons (Nikishov 1962; Gould 1966; Stecker 1992; Biller 1995) is considerably greater than the range of UHE cosmic rays so attenuation is negligible. Thus, such gamma radiation should be an excellent probe of higher energy phenomena which would be otherwise be opaque. The starting point for guessing the gamma-ray flux is the cosmic ray spectrum measured by the Fly's Eye

Experiment (Bird *et al.* 1994):

$$J(E) = 5.13 \times 10^{21} \ \ (E/1 \ \mathrm{ev})^{-3.07} \ \ cm^{-2}s^{-1}sr^{-1}eV^{-1} \ \ (E > 10^{17}\mathrm{eV}).$$

For energies greater than 3×10^{20} eV, the extrapolated integral flux is 1×10^{-21} particles/cm²-s-sr. For the one event measured at the end of the spectrum, the corresponding flux from a point source is 6×10^{-20} particles/cm²-sec. A plausible assumption, based on the behavior of AGNs, is a constant νF_ν distribution extending downwards in energy to the TeV range. If the total available energy is partitioned roughly equally between gamma rays and cosmic rays, the anticipated gamma-ray flux would be in the neighborhood of 6×10^{-11} γ/cm²-sec at 3×10^{11} eV. This value is in the range of sensitivities achievable with the Whipple gamma-ray telescope at Mt. Hopkins, AZ (Reynolds *et al.* 1993) which can detect the flux from the Crab Nebula ($\approx 10^{-10}\gamma$/cm²-sec) with a significance of 7 σ in one hour.

These considerations led us to conduct an exploratory experiment to see if an enhancement of gamma rays could be detected from the direction of the Fly's Eye UHE cosmic-ray event (Bird *et al.* 1995). This particular event was selected because the error box was small and the position on the sky was convenient for observations at small zenith angle where the atmospheric Čerenkov technique is most sensitive. The celestial coordinates of this event were

$$\alpha(1950) = 85.2° \pm 0.5°, \ \ \delta(1950) = 48.0° \pm 6.0°$$

2. Observations

The object of this experiment was to locate a possible point source of TeV radiation correlated with the direction of the Fly's Eye event. Normally, TeV observations at Whipple are conducted with accurate *a priori* knowledge of source locations. However, it is possible, using techniques akin to computer tomography, to reconstruct an unknown point source location from statistical analysis of the data as was first shown in a paper by Akerlof *et*

al. (1991). This technique has been refined further and used to search for TeV photons from gamma-ray bursts (Connaughton *et al.* 1997a) and supernova remnants (Buckley *et al.* 1997).

Because of the uncertainty in the location of the topological defect, 12 overlapping regions, each centered on the Right Ascension 86.01° (J2000), were observed with the 10m reflector. Figure 1 shows the region of sky covered by the Whipple observations. The letters in the box indicate the central point of each region. The declinations range from 42.51° (Position A) to 53.51° (Position L) in 1° increments so that, with the 3.5° field-of-view of the camera, some overlap occurred between adjacent regions. Each position was observed for two 28 minute periods. Observations were made during 4 nights in December 1995. The data rate of an air shower Čerenkov telescope is affected by telescope elevation and sky conditions and hence the sensitivity and energy threshold of the survey varied with position.

3. Analysis

Generally, observations of a point source whose location is known are analyzed by searching for excess gamma-ray candidates from the source direction compared to a nearby patch of sky. Control observations of a position offset in right ascension by 28 minutes from the source location are made with the telescope at the same elevation as the source observations, and the excess of selected events from the source observations (ON data) relative to the control (or OFF source) data gives a measure of the photon flux from the source. In this analysis, the coordinates of the source are unknown and there are no control observations. One must, therefore, assume that each location on the sky is a potential source, and look for an unexpectedly large number of gamma-ray-like events in each of the 28 minute scans from some point in the field-of-view.

Standard routines (Reynolds, *et al.* 1993) were used to flat-field and parameterize the data. Events in the data files are comprised of the digitized signals registered

by the 109 photomultiplier tubes in the focus box of the 10m reflector. For each shower produced, a moment-fitting analysis is used to obtain a set of image parameters characterized by *width, length, light concentration,* and *size* (total number of digital counts). These parameters represent the two angular aspects of the shower light distribution, its compactness and total energy, respectively. A combination of these image parameters has proven effective in discriminating against the hadronic background by selecting only those events with the appropriate direction for a particular source and the shape characteristic of gamma-ray showers. The Supercuts technique described in (Reynolds, *et al.* 1993) rejects 99.7% of the recorded background while keeping 50% of the gamma rays. In this analysis, gamma-ray-like events are selected on the basis of image shape, using *width* (semi-minor axis of ellipse) and *length* (semi-major axis) cuts. The development of image selection criteria and assessment of non-source-centered capabilities of the 10m reflector are given in (Connaughton *et al.* 1997b). In this analysis gamma-ray-like events are selected suing the following Supercuts shape criteria:

$$0.073° \; < width \; < 0.15°$$
$$0.16° \; < length \; < 0.30°$$

where the width and length are the semi-minor and semi-major axes of the elliptical image fitted to each event. In addition, a minimum size of 400 dc (approximately 400 photo-electrons) is required, corresponding to an energy threshold of around 350 GeV.

The orientation of the ellipse fitted to each image is represented by its major axis, and the most likely point-of-origin of the shower progenitor on the field-of-view lies on this axis at a distance d in degrees related to the ellipticity of the image:

$$d = 1.7 - 1.7(width/length) \tag{1}$$

This algorithm yields two points, one on either side of the center of the image, and

is considered to be accurate to about 0.3° either side of each point (Akerlof *et al.* 1991, Connaughton *et al.* 1997a). A grid of bins 0.1° × 0.1° in size is constructed to cover the field-of-view of the camera and beyond. The grid extends 3° each side of the center so that the sensitivity of the technique outside the geometrical field-of-view can be exploited. Each bin which lies within 0.3° of either point-of-origin for an event is incremented.

The two data files taken on each position comprise the 'ON' source data. Control, or 'OFF source', data are obtained by averaging the grid bin occupancies of 'ON' files taken at similar elevations. Three groups of control data were defined: 5 of the 24 observations at telescope elevations below 64°, 12 between 64° and 71°, and the remaining 7 at higher elevations. The excess at any grid point (i, j) in the ON data is found relative to the corresponding point in the control observations using the equation:

$$\sigma_{i,j} = \frac{(N_{ON} - p \times N_{OFF})}{\sqrt{(N_{ON} + p \times N_{OFF}/N_{BG})}} \tag{2}$$

where N_{BG} is the number of observations that were averaged to make up the background contour map. A normalizing factor p is applied to account for the differences in the durations of the ON and OFF observations. In figure 2, the resulting contours on the grid represent the significances of the excess of photon-like events over 56 minutes from each of the positions observed.

4. Results

Figure 2 shows the contour plots for positions D to I, typical of all 12 observations. The contours begin at 1σ and increment in 1σ steps. Given that there are no significant excesses in any of the bins in the ON data relative to the control data, one can calculate an upper limit to the flux from each of the positions observed. The collection area above 350 GeV of the 10 m telescope for a source in the center of the camera is $5.4 \pm 0.9 \times 10^8$ cm^2 (Connaughton, *et al.* 1997b). This is larger than the collection area given in, for example,

(Reynolds *et al.* 1993), because of the less restrictive orientation criteria applied to these non-source-centered observations. Using the total number of shape-selected events in the ON and control files, the 99.9% maximum likelihood value for emission from all positions are presented in Table 1. The errors reflect the uncertainty in the collection area of the 10m reflector and the statistical nature of variation in selected event rates within each control data group. These limits apply to emission above 350 GeV from a source in the center of the camera. In calculating the limits from any other point in the field-of-view, a scaling factor must be used to account for the decreasing gamma-ray efficiencies away from the center of the camera (Connaughton, *et al.* 1997b). A lower flux upper limit is derived for sources which might lie at the camera's center than for those at the edge of the camera. The upper limits as a function of source offset are shown in Figure 3. The two outer lines represent the lowest and highest limits that can be set, the middle line shows the limits with the smallest error bars (the most homogeneous control group), the difference being due to the statistical variations in event rates and the diminishing efficiency of Supercuts with decreasing telescope elevation.

5. Interpretation

The lack of a detectable gamma-ray signal from the direction of the Fly's Eye ultra-high energy cosmic ray event does not lead to any clear-cut conclusion. First of all, the sky coverage was limited to the cosmic ray error box alone which does not include effects of possible curvature of the trajectory by intervening extragalactic magnetic fields. Such fields might bend these particles by as much as 5° or more from the original source direction. Furthermore, it was tacitly assumed that the particle acceleration process operates continuously to generate energetic particles. If instead, these particles are created in short bursts, the cosmic ray arrivals will surely lag the gamma-ray photons since they will be delayed by the additional path length due to magnetic curvature so that no follow-up observation can succeed. In the former case with small magnetic deflections and constant

flux, we can make some comparisons with theoretical estimates. Protheroe and Stanev (Protheroe & Stanev 1996) have estimated particle fluxes from the decay of GUT-scale particles with masses $\simeq 10^{14}$ GeV. Their results for gamma-rays and protons are shown in figure 4 taken from their paper. The point at 3×10^{11} GeV shows the cosmic ray flux inferred from the single highest energy Fly's Eye event, averaged over 4π steradians. We do not know if this one event comes from a particularly bright compact source or simply represents one count from an otherwise isotropic distribution. However, a second event with an energy of 1.2×10^{11} GeV measured by the Yakutsk Array *et al.* (Efimov *et al.* 1991) was detected at coordinates less than $8°$ away. Similar correlations have been observed by Hayashida *et al.* (Hayashida *et al.* 1996). Thus, the ultra-high energy cosmic ray sky may in fact be highly anisotropic, a major focus of interest for the proposed AUGER experiment (Auger Collaboration 1996). If true, the Fly's Eye flux could be directly compared with the TeV gamma-ray flux limits determined above. In figure 4, the Fly's Eye event at E $=$ 3×10^{20} eV has been converted to a flux value by assuming a 4π steradian solid angle and an energy bin 7.3×10^{19} eV wide. To compare with the Whipple gamma-ray flux limits obtained here, we can similarly divide by 4π steradians and an effective energy bin of 350 GeV (from the assumption of a constant $\nu F(\nu)$ spectrum). This is depicted as the lower of the two Whipple limits in figure 4. An alternative upper limit can be derived from the general upper limit derived from the Whipple experiment on diffuse gamma rays. Based on Monte Carlo simulations of the off-axis efficiency, the effective solid angle-collection area of the detector for diffuse gamma rays (or electrons) is 48 m^2-sr (Connaughton *et al.* 1997b). The number of events passing the gamma ray selection criteria is < 0.2 per minute leading to an upper limit of 150 (E/1 GeV)$^{-2.7}$ $photons/m^2 - s - str$. This is plotted in figure 4 as the greater of the two Whipple limits. The results for Whipple and HEGRA (Karle 1995) are displayed at energies of 350 GeV and 100 TeV respectively. Although the Whipple limit is about four times larger than the HEGRA result, it is 20 times closer to the gamma-ray estimates of Protheroe and Stanev. One might be concerned that the TeV photons migrating to Earth may be considerably scattered from the original ultra-high

energy particle direction. However the threshold energy is sufficiently low that relatively few gamma-rays will be produced with transverse momenta of 1 GeV or more with respect to the primary direction and thus outside the acceptance of our gamma-ray selection criteria.

6.   Emission from 3C147

The most conservative assumption of the origin of the highest energy cosmic rays is that they are accelerated in the jets of Active Galactic Nuclei (AGN). The detection of TeV gamma-ray emission from the two AGNs (Markarian 421 and 501) (Punch et al. 1992; Quinn et al. 1996) supports the notion of high energy particle acceleration within some AGN. However within the error box of the Fly's Eye event there is no AGN within 50 Mpc.

The most interesting extragalactic object within the error box is the AGN, 3C147, one of the earliest optical quasars discovered ($z = 0.545$). It is also very bright in radio and X-rays (luminosity in both bands in excess of 8×10^{44} $ergs - s^{-1}$). It also has a strong Faraday rotation. Thus, apart from its redshift, this object is a prime candidate for identification as the source of the Fly's Eye event and possibly the nearby Yakutsk event.

If 3C147 was the source of the high energy particles, then it is likely that it would also be a source of TeV gamma-rays. However the redshift of 3C147 would suggest that there might be considerable absorption of TeV gamma-rays by pair production on infrared photons in intergalactic space. (Nikishov 1962; Gould 1966; Stecker 1992, Biller 1995) Observations of 3C147 (and two other AGNs) were made in the 1963-64 observing season in Glencullen, Ireland by a combined Irish-U.K. team using a small atmospheric Čerenkov system with an energy threshold of 5 TeV (Long *et al.* 1964). A signal was detected at the 3 σ level (corresponding to a flux of 1×10^{-10} photons- $cm^2 - s^1$). This would have indicated an incredible gamma-ray luminosity of 5×10^{47} ergs-s^{-1}. However this emission was not verified and was not seen in any MeV-GeV gamma-ray telescope experiment either.

3C147 (R.A.=05 39, Dec.=+49 49) was included in the survey with the Whipple

telescope reported above (G, Figure 2). In addition a series of tracking observations were made with 3C147 in the center of the field of view for maximum sensitivity. Six hours of observation under optimum conditions gave no indication of a signal and an upper limit of 1.8×10^{-11} photons-cm$^2 - s^1$ was derived. Given the greater sensitivity of the Whipple telescope it appears most likely that the Glencullen result was a statistical fluctuation. Hence there is no evidence from TeV gamma-ray observations to support the identification of 3C147 as the cosmic ray source.

7. Discussion

The experiment described above was an exploratory effort to correlate TeV gamma-rays with UHE cosmic rays. No evidence has been found for a steady emission source at a flux level that might be expected for such an object. From generic physics considerations, the co-production of gamma-rays and UHE cosmic rays seems almost inevitable so an extension of these experimental efforts is highly warranted. By increasing the extent of the search fields and the observation time, one could probe more deeply while providing a greater margin for the unknown magnetic deflection of the UHE primary on its trajectory to the Earth.

The more likely scenario is that the processes that generate UHE cosmic rays are episodic. This makes the correlated detection of VHE gamma-rays considerably more difficult since the cosmic rays will lag the photons by intervals of the order of 100 years (Waxman & Coppi 1996). New detectors such as MILAGRO and GLAST with wide fields of view are particularly suited for investigating the existence of such transient gamma-ray fluxes. More generally, the study of short astrophysical transients has been barely explored, even at optical wavelengths.

UK, and by Forbairt in Ireland.

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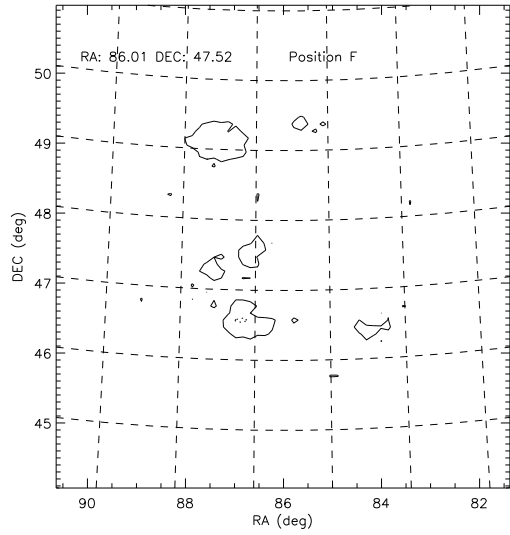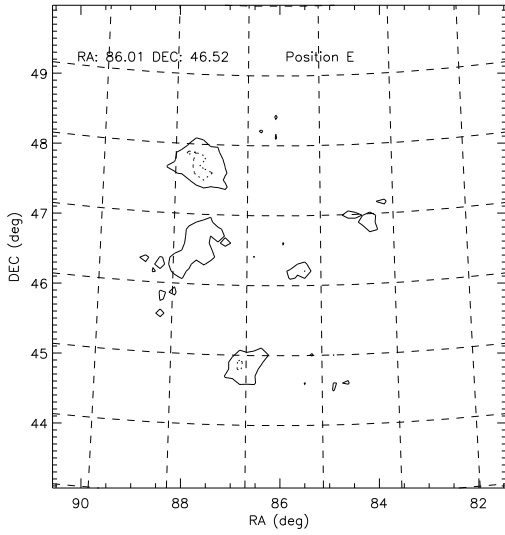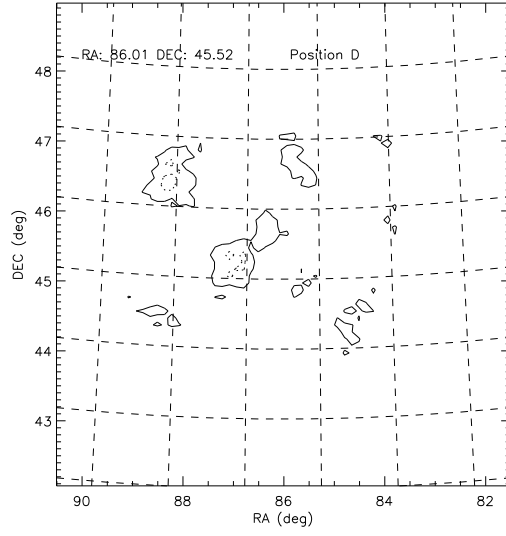| Position	Flux $(\times 10^{-11}$ erg cm^{-2} s$^{-1})$	Flux $(\times 10^{-11}\gamma$ cm^{-2} s$^{-1})$
A	3.5 ± 1.2	7.3 ± 2.5
B	3.6 ± 1.0	7.5 ± 2.1
C	4.4 ± 1.1	9.2 ± 2.3
D	2.7 ± 1.1	5.6 ± 2.3
E	5.1 ± 2.3	10.6 ± 4.8
F	7.7 ± 3.1	16.0 ± 6.5
G	3.0 ± 2.2	6.3 ± 4.6
H	4.9 ± 1.5	10.2 ± 3.1
I	3.6 ± 1.2	7.5 ± 2.5
J	3.9 ± 1.4	8.1 ± 2.9
K	1.4 ± 2.2	2.9 ± 4.6
L	1.5 ± 1.3	3.1 ± 2.7

Table 1: Upper limits for E > 350 GeV
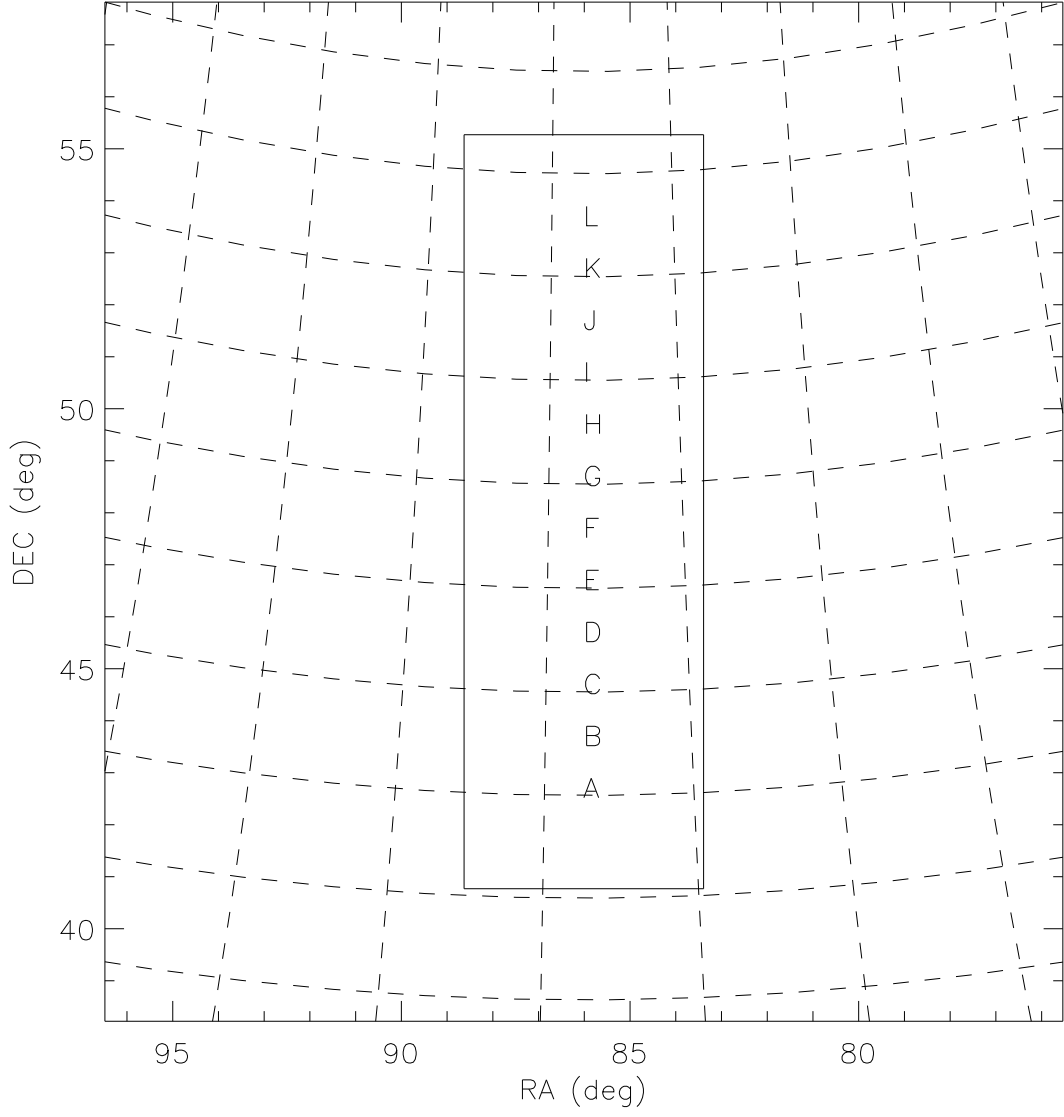
Fig. 1.— Whipple coverage of the area surrounding the Fly's Eye event. Each position is centered on RA=86.01° and separated from the next in declination by 1°. Since the field-of-view is 3.5°, there is some overlap between adjacent positions.

RA: 86.01 DEC: 45.52   Position D

RA: 86.01 DEC: 46.52   Position E

RA: 86.01 DEC: 47.52   Position F

RA: 86.01 DEC: 48.52   Position G

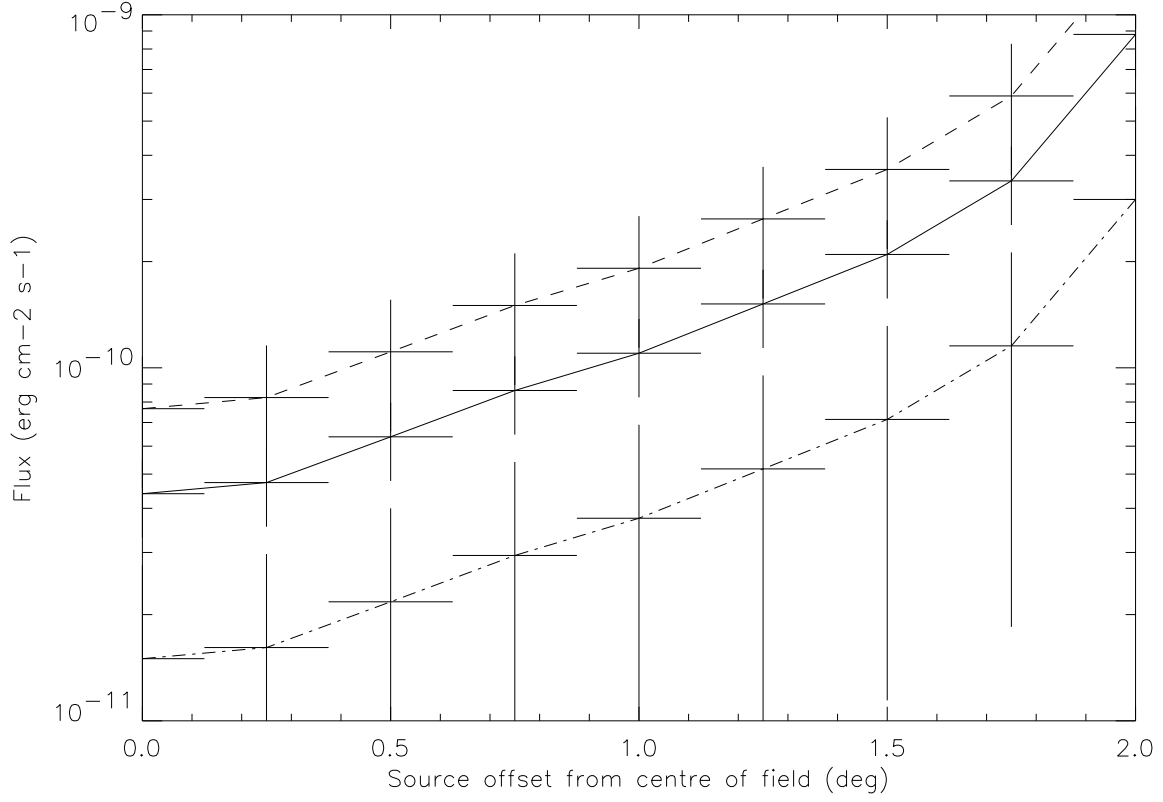RA: 86.01 DEC: 49.52   Position H

RA: 86.01 DEC: 50.52   Position I
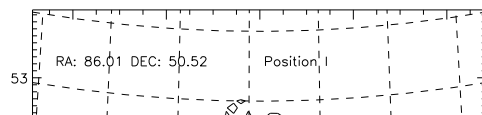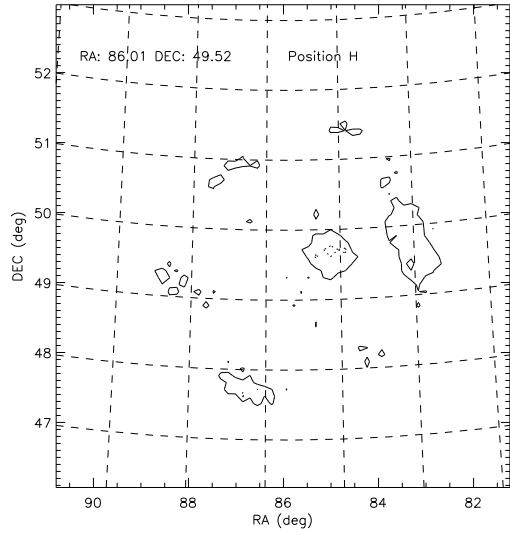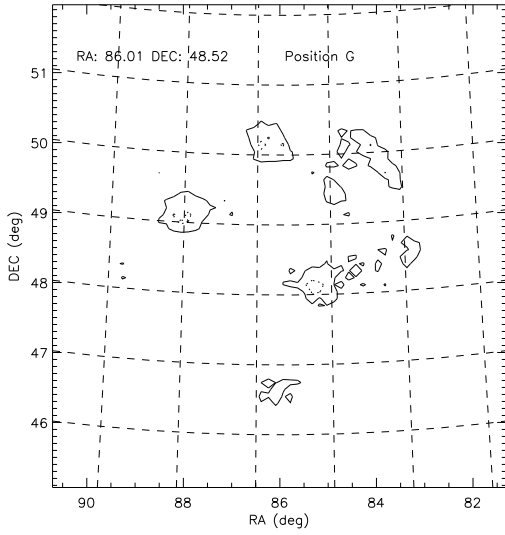
Fig. 3.— Upper limit to the flux above 350 GeV from topological defects for a point source over the field-of-view of the 10m reflector : Position C (solid), Position F (dashed) and Position L (dot-dashed).
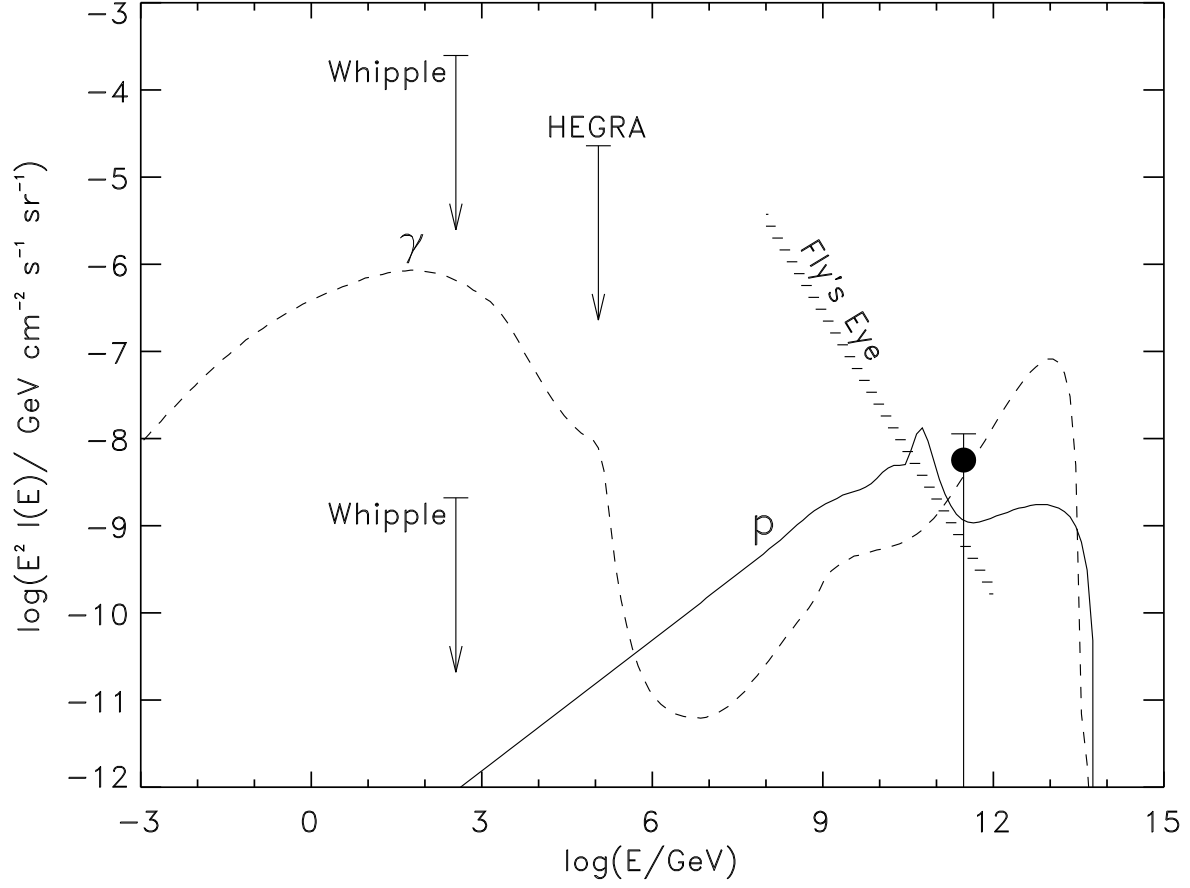
Fig. 4.— Plot of estimated γ-ray and proton fluxes from topological defects taken from Figure 1 of paper by Protheroe and Stanev. The Fly's Eye event at 3×10^{20} eV is plotted with a filled circle. The γ-ray upper limits are described in the text. The Whipple points refer to this experiment; the HEGRA data is from Karle (1995).